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Classification and petrology of six equilibrated ordinary chondritic meteorite finds from Western Australia

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Abstract

Six stony meteorite finds from Western Australia are described and classified. The meteorites: Baandee (H5), Jeedamya (H4), Wooramel (L5), Mount Margaret (L5), Nimberrin (L6) and Millrose (L6), are all equilibrated ordinary chondrites. Bulk chemical analyses and total iron contents (Fe_T) of Baandee (29.18 wt.%), Jeedamya (28.28 wt.%), Mount Margaret (22.4 wt.%) and Wooramel (22.28 wt.%) are presented.

The chondrites display degrees of alteration attributable to pre-terrestrial shock-loading appropriate to facies b (Baandee, Jeedamya, Mount Margaret), facies d (Nimberrin, Millrose) and facies d-e (Wooramel) of the Dodd and Jarosewich (1979) classification. Estimates are made of the P/T levels of shock alteration, and the post-shock thermal histories of the meteorites are discussed.

Introduction

As the result of a generally arid climate, Western Australia has proved to be one of the most prolific areas of the world for meteorite finds (Bevan and Binns 1986). The special conditions occurring in the Nullarbor Region of Western Australia, that has yielded more than half of the total number of meteorites known from the State, have been described by Bevan and Binns (1989 a, and b). However, meteorites continue to be found throughout Western Australia.

In this paper, details are presented of the discovery, classification, petrology and chemistry of six previously undescribed and distinct ordinary chondrites, viz. Baandee, Jeedamya, Wooramel, Mount Margaret, Millrose and Nimberrin. In accordance with guidelines on meteorite nomenclature, the meteorites take the names of the geographical localities closest to the sites of their discovery (Figure 1a).

Circumstances of find, and morphology

Baandee: The discovery in 1967 of this freshly crusted stony meteorite was reported by McCall (1972) and is listed by Graham *et al.* (1985). The meteorite (WAM 13225) was found by Mr R. Spillman at a locality (31° 37'S., 118° 02'E) on Land Unit 13929, adjacent to 'Hunters Dam', approximately 6.8 km ESE of Baandee Railway Station. Subsequently, the discovery was linked to a fireball accompanied by sonic phenomena reported nearby in 1961 or 1962 (McCall 1972; Graham *et al.* 1985) but the evidence is not conclusive.

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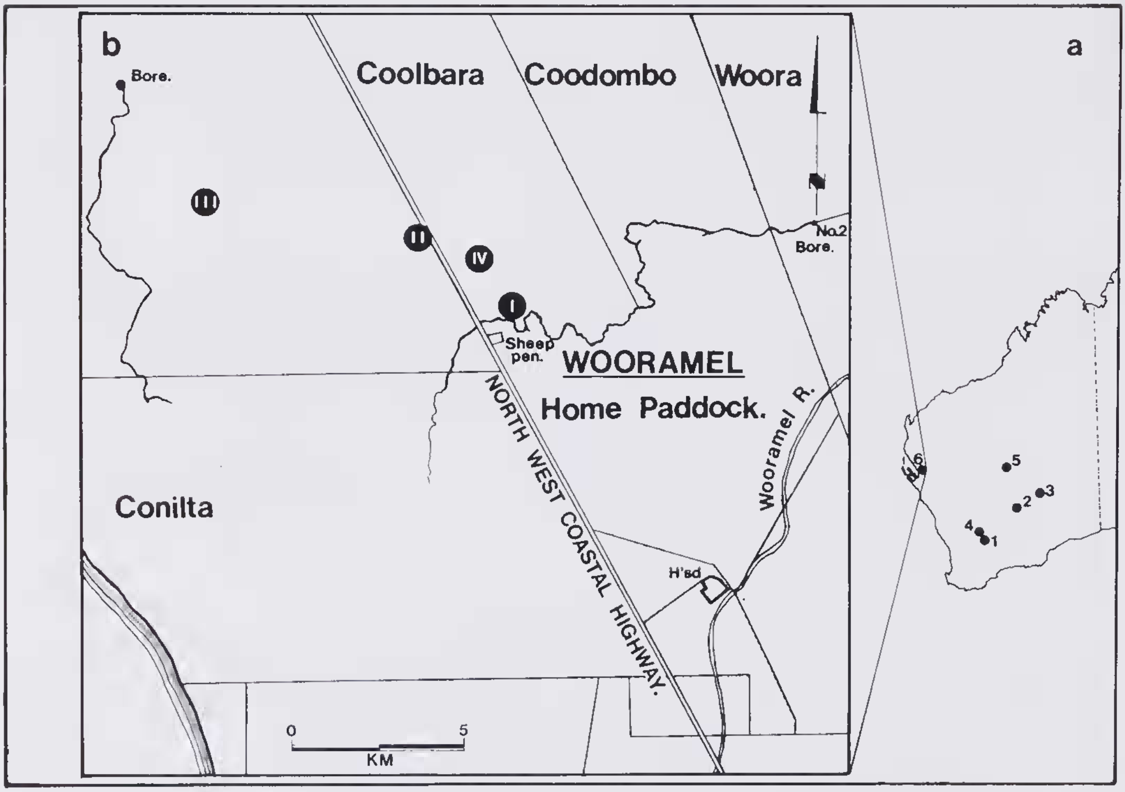

Figure 1a. Localities of discovery of the Baandee (1), Jeedamya (2), Mount Margaret (3), Nimberrin (4), Millrose (5) and Wooramel (6) meteorites from Western Australia.

1b. Enlargement of the area surrounding Wooramel Station (q.v.) showing the distribution of the four known masses of the Wooramel meteorite shower.

The meteorite (Figure 2a) has a flatly domed, elongated shape and clearly remained orientated during atmospheric passage. The posterior surface is flat and coated with thick (>0.5 mm), stippled fusion crust. The anterior surface is generally convex, curves sharply towards the posterior surface and is decorated with radial flow lines. One end of the stone is truncated by a scalloped surface from which a fragment may have become detached during atmospheric flight.

On cut surfaces, the meteorite displays conspicuous chondrules up to 2 mm in diameter and abundant, fresh particles of metal set in a faintly iron-stained, friable crystalline silicate matrix.

Wooramel: In April 1969, Mr R.A. Hall, the owner of Wooramel Station (q.v.) (25° 44′S., 114° 17′E.), found a large stony meteorite close to the Station's sheep pens (25° 39′S., 114° 13′E.). The pens are approximately 10 km NW of Wooramel Homestead, on the eastern side of the North West Coastal Highway (Figure 1b). The meteorite (WAM 13518), weighing 45 kg, was buried to a depth of 3 cm in red, loamy soil.

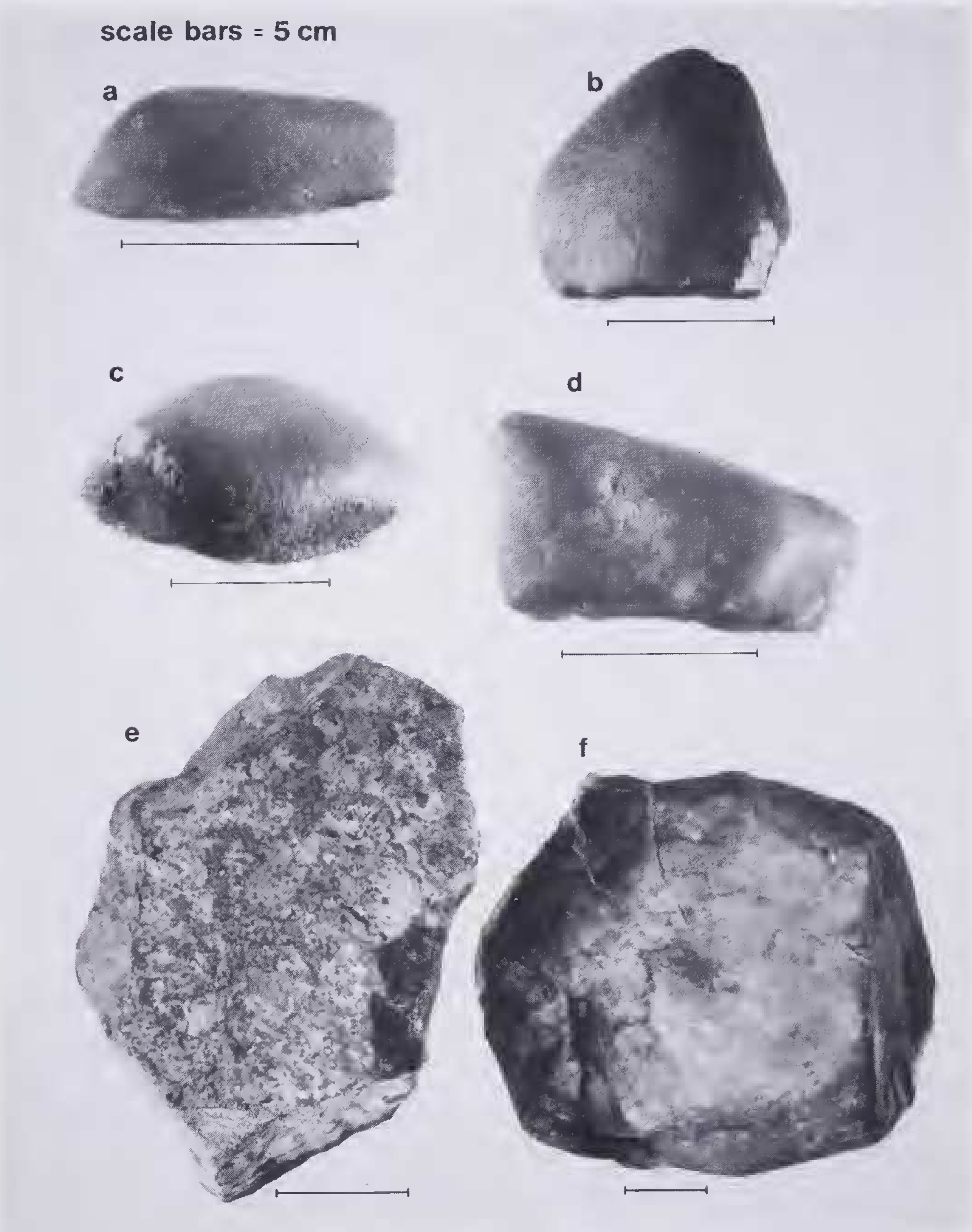

Figure 2. The Baandee (a), Jeedamya (b), Mount Margaret (c), Nimberrin (d), and Millrose (e) meteorites, and (f) the main mass (no. 1) of the Wooramel meteorite shower.

Subsequently, in July and August 1971 and in June 1976, in the general area of the first discovery Mr Hall found three more individuals (WAM 13391; 13519; 13455) of the same meteorite weighing 9.4, 6.35 and 10.25 kg, respectively. The find-sites of the four meteorites (Figure 1 b), designated Wooramel I-IV in order of discovery, are roughly aligned over a distance of approximately 9 km. The size distribution of the masses suggests an atmospheric trajectory for the meteorite fall in an ESE direction before fragmentation in the lower atmosphere.

All the individuals of the shower have irregular, polygonal shapes. The two larger individuals (Wooramel I and IV) are well preserved although the smallest (Wooramel III) is deeply weathered. With the exception of Wooramel I (Figure 2f), which is completely crusted, all the remaining individuals display fractured surfaces, and Wooramel IV is approximately half of an individual.

On cut surfaces, the meteorites display abundant flecks, and occasional veins, of fresh metal, and indistinct chondrules. The silicate minerals are extensively stained brown and most individuals of the shower display a zone of severe terrestrial weathering extending to a depth of 1-3 cm below the level of the crust. The deep interiors of the larger stones remain well preserved.

Jeedamya: In November 1972, Mr R. Blizzard found a flight-orientated meteorite weighing 914 grams in a shallow (1 cm) depression in sandy soil on Jeedamya Station. The locality (29° 35′S., 121° 10′E.) is 0.6 km south of the intersection of the boundary fence of Jeedamya Station and the Menzies-Leonora road.

The meteorite (WAM 13191 Figure 2b) is pyramidal in shape with a smoothly convex anterior surface and three, less regular, posterior surfaces which form the apex of the pyramid. Except for some broken edges, the stone is covered with a well preserved, dull black fusion crust. The anterior surface is marked with flow lines which radiate from the centre and is covered with thinner (0.2 mm) fusion crust than the three posterior surfaces (1 mm). The interior of the meteorite is light grey in colour, but mottled locally with minor, brown iron oxide staining. Abundant particles of metal, and chondrules up to 3 mm in diameter are visible on cut surfaces.

Mount Margaret: In December 1972, a fresh stony meteorite was found on the north shore of Lake Carey (28° 50′S., 122° 11′E.) *c.* 32 km SW of Laverton. The finder, Mr Cyril Barnes of Mount Margaret Mission, sent the meteorite to the Western Australian Museum via Mr R.C. Botrell in 1973. The original weight of the stone was not recorded, but was approximately 890 grams.

Mount Margaret (WAM 13358 Figure 2c) is an ellipsoidal, flight-orientated individual. The anterior surface is smoothly convex and marked with radial flow-lines. The edge of the stone between the anterior and posterior surfaces is covered with a thick (2 mm) accumulation of fusion crust forming a ‘flange’. The posterior surface, which is also slightly convex, is covered with thick scoriaceous crust. In a few places along the flange of the stone the crust has flaked away exposing the interior.

Prominent chondrules up to a maximum of 4 mm in diameter, and homogeneously distributed grains of metal are visible on cut surfaces. Locally, minor terrestrial oxidation has stained the silicate minerals a light brown colour.

Nimberrin: While ploughing in August 1970, Mr R. Spillman found a single, crusted stony meteorite weighing 786.4 grams at a locality (31^0 31′S., 117^0 58′E.) about 0.8 km NNW of Nimberrin Homestead. The meteorite (WAM 13356 Figure 2d) is polygonal and covered predominantly with smooth, well preserved primary fusion crust. One irregular, crusted surface is pitted and probably represents a fracture surface from which a fragment was detached during atmospheric flight.

Generally, the interior of the meteorite is heavily stained brown with the products of extensive terrestrial oxidation of metal. However, in the deep interior, at a depth of 2-3 cm below the crust, a small portion of the meteorite remains comparatively fresh and displays indistinct chondrules of up to 3 mm in diameter.

Millrose: In February 1984, a large stony meteorite weighing 7.464 kg was found on Millrose Pastoral Station by the owner, Mr Rex Ward. The meteorite, which was partially buried to a depth of 9 cm in the soil, was found at a locality (26^0 20′S., 121^0 E.) about 9.5 km on a bearing 33^0 from Millrose Homestead (q.v.) on the fence line between 'Old Camp' and 'Tommy' bores. Millrose (WAM 13632 Figure 2e) is an elongate, polygonal stone and the interior of the meteorite has been extensively altered by terrestrial oxidation.

Analytical procedures

Polished thin sections were prepared and examined microscopically in transmitted and reflected light. Silicates were analysed using a MAC energy dispersive electron microprobe operated at 15 kV and 20.00 nA. Analyses were corrected using the programme developed by Ware (1981). A minimum of ten grains each of olivine and pyroxene were analysed in each meteorite. In addition, grains of plagioclase feldspar and diopsidic clinopyroxene were analysed where these were sufficiently large to allow mircroprobe analysis. Petrologic types were assigned to each meteorite according to the classification of Van Schmus and Wood (1967) and a 'facies' of alteration as the result of pre-terrestrial shock-loading according to Dodd and Jarosewich (1979).

Bulk chemical analyses were performed on aliquots of Baandee, Jeedamya, Mount Margaret and Wooramel. The method of analysis, described by Moss *et al.* (1967), uses magnetic mineral separation followed by selective attack of dry chlorine on kamacite and sulphide, leaving silicates and taenite essentially unaffected. The technique allows major and some trace elements to be determined in a number of separate fractions of chondritic meteorites.

Owing to the deeply weathered condition of Wooramel and the presence of abundant iron oxide ('maghemite') from the terrestrial alteration of metal, slight modifications of the chlorination method were used in the analysis of this meteorite. The entrainment of terrestrial oxidation products with silicates and their sluggish response to attack by chlorine resulted in incomplete physical and chemical separation of the magnetic and non-magnetic components of the meteorite. A partial separation of terrestrial oxides, silicate and metal was achieved by repeated grinding and sieving and the fresh metal chlorinated separately. Some oxide remained with silicates and contributed to the volatile chlorides in this fraction. Separated 'maghemite' was analysed and the results (FeO, Fe_2O_3 and NiO) included with silicates as a total oxide fraction.

Classification and petrology

The essential mineralogical, petrographic and structural features of the six meteorites are detailed in Table 1 and microprobe analyses of their major constituent minerals are given in Table 2. Bulk chemical analyses and normative compositions of Baandee, Jeedamya, Mount Margaret and Wooramel are reported in Table 3.

Baandee is a moderately recrystallized chondrite. The bulk chemical composition (Table 3), total Fe content (29.18 wt %) and compositions of the principal ferro-magnesian silicates (olivine $Fa_{18.7}$; orthopyroxene $Fs_{16.7}$ $Wo_{1.1}$) show that Baandee belongs to the H-group of ordinary chondrites. Although the meteorite displays prominent chondrules, microscopically, the chondrules and matrix are partially integrated by recrystallization. Plagioclase feldspar ($An_{11.5}$ $Ab_{82.9}$ $Or_{5.6}$) occurs as small, turbid crystallites in the mesostases of chondrules and throughout the matrix (Table 1). Uniform mineral compositions, the presence of generally microcrystalline plagioclase, and the predominance of orthorhombic pyroxene indicates that Baandee belongs to petrologic type 5 of the Van Schmus and Wood (1967) classification.

Throughout the meteorite, minerals display evidence of slight alteration as the result of pre-terrestrial shock-loading. Silicates are generally fractured and, between crossed polars, display weak undulose extinction. Maskelynite was not observed, and the level of shock alteration is consistent with 'facies b' of the Dodd and Jarosewich (1979) classification.

Jeedamya comprises abundant, closely packed and easily recognizable chondrules set in a fine grained granular matrix. The total iron content (28.28 wt %) of the meteorite (Table 3) shows that Jeedamya belongs to the H-group of ordinary chondrites.

Microscopically, olivine is more abundant than low-Ca pyroxene, the latter frequently displaying relic twin lamellae. Accessory diopside occurs as lamellae within, or rims to, large grains of orthopyroxene and as acicular crystals in the mesostases of some chondrules. The mesostases of chondrules are composed variably of microcrystalline material and turbid, grey to brown, devitrified glass.

Microprobe analyses (Table 2) show that the mean composition of olivine in Jeedamya is $Fa_{19.5}$ (N=37, σ=0.18). The compositions of low-Ca pyroxenes are slightly variable ranging from $Fs_{16.1-17.7}$. The mean composition of pyroxene is $Fs_{17.2}$ (N=19 , σ=0.47), and the wollastonite contents of grains vary from 0.6-1.3 mol. %.

McCall (1972) classified Jeedamya as an H6 chondrite. However, the lack of crystalline plagioclase feldspar and abundance of twinned clinopyroxene indicate that Jeedamya is petrologic type 4. The mean Wo content of pyroxene (0.9%) (Table 2) in Jeedamya lies within the range (0.4-1.2 mol. %) commonly encountered in type 4 chondrites (Scott *et al.*, 1986). However, moderate integration of chondrules and matrix indicate that the meteorite may be transitional between types 4 and 5.

Table 1. Essential mineralogical, petrographic and structural features of six ordinary chondrites from Western Australia.

METEORITE	CLASS	CHONDRULES						MINERALOGY, PETROGRAPHY AND METALLOGRAPHY									
		CLARITY	Chondrule Types					Olivine	Ortho-pyroxene	Twinned clino-pyroxene	Diopside	Plagioclase feldspar (grain size)	α-kamacite	γ-taenite	troilite	other minerals	Structural remarks
			Size range (Av. size) mm.	porphyritic olivine/pxn	barred olivine	radiating pyroxene	other										
Bandee	H5b	recognizable	0.2-2 (0.6)	✓	✓	✓		weak undulose extinction	✓	rare grains	rare grains	undulose extinction (<50 μm)	Neumann bands	normal, zoned	deformation twins	chromite	
Jeedamya	H4b	closely packed, recognizable	0.2-3 (0.5)	✓	✓	✓	micro-porphyritic	weak undulose extinction	✓	rare grains	rims to opx	rare turbid grains (<50 μm)	abundant Neumann bands	zoned + plessite	polycrys-talline, deformation twins	chromite	metal grains deformed
Moorsmel	L5d-e	recognizable	0.2-2 (0.5)	✓	✓	✓		strongly undulose extinction, incipient mosaicism	✓	common grains	✓	undulose extinction + maskely-nite?	partially transformed to α_2	partially decomposed to plessite	strongly polycrystal-line	chromite	melt poc-kets, extensive metal/ troilite melting and veining
Mount Margaret	L5b	recognizable	0.3-4 (0.6)	✓	✓	✓	excentro-radial	weak undulose extinction	✓	rare grains	✓	small grains	Neumann bands	normal, zoned	locally poly-crystalline, deformation twins	chromite, rare grains native copper	
Nimberrin	L6d	poorly defined, thorough recrystal-lized	-	✓	✓	✓		strongly undulose extinction, incipient mosaicism	✓	absent	✓	converted to maskelynite	recrystallized	abundant cellular plessite	strongly poly-crystalline	chromite, merrilite	melt poc-kets, abundant metal/ troilite melting
Millrose	L6d	poorly defined, recrystal-lized	-	✓	✓	✓		strongly undulose extinction, mosaicism	✓	absent	✓	large grains (>50 μm) un-dulose ex-tinction, partially converted to maskelynite	Neumann bands, incipient transforma-tion to α_2	severe shear deforma-tion, incipient transfor-mation of plessite	poly-crystalline, deformation twins	chromite	melt pockets, metal/ troilite melting

Table 2: Representative analyses and compositional ranges of olivine and low-Ca orthopyroxene in six ordinary chondrites from WA

		Baandee	Jeedamya	Mt Margaret	Millrose	Wooramel	Nimberrin
olivine							
	SiO_2	38.67	38.26	37.80	38.19	38.08	37.42
	FeO*	17.54	17.99	22.22	22.47	22.59	23.23
	MnO	0.44	0.55	0.57	0.60	0.48	0.56
	MgO	43.16	43.14	40.14	39.32	39.05	38.91
	CaO	—	—	—	—	—	—
	Total	99.81	99.94	100.73	100.58	100.20	100.12
Range							
No. of anals.		15	37	15	10	14	10
mean Fa(mol%)		18.7	19.5	24.0	24.8	24.9	25.5
	%MD	1.7	1.0	1.0	2.0	1.7	1.5
orthopyroxene							
	SiO_2	56.21	55.81	55.41	54.93	55.50	55.21
	TiO_2	—	—	—	0.37	—	—
	FeO*	11.07	11.14	13.62	13.58	13.99	14.32
	MnO	0.44	0.48	0.58	0.61	0.58	0.42
	MgO	31.94	31.43	29.53	28.94	29.68	29.05
	CaO	0.53	0.52	0.53	0.77	0.67	0.55
	Total	100.19	99.38	99.67	99.20	100.42	99.55
Range							
No. of anals.		10	19	10	10	10	10
mean Fs (mol%)		16.7	17.2	20.9	21.4	21.3	22.3
mean Wo (mol%)		1.1	0.9	1.1	1.5	1.3	1.5

* All Fe as FeO — = not detected % MD = percentage mean deviation.
Analytical conditions: MAC E.D.S. electron microprobe operated at 15 kV and 20 nA.
Standards employed; independently analysed olivine and pyroxene. Analyst A.W.R. Bevan.

In Jeedamya, minor modifications of both silicate and metallic minerals (Table 1) as the result of shock-loading indicate a level of shock alteration appropriate to 'facies b' of the Dodd and Jarosewich (1979) classification.

Wooramel contains abundant, tightly packed and irregularly shaped chondrules set in a medium grained crystalline matrix. The bulk chemical composition (Table 3), with total iron content of 22.28 wt %, and the compositions of olivine ($Fa_{24.9}$) and pyroxene ($Fs_{21.3}$. $Wo_{1.3}$) (Table 2) classify Wooramel as an L-group ordinary chondrite (Van Schmus and Wood, 1967). Although well integrated with the matrix, chondrules remain distinct by virtue of their well preserved internal textures. The mesostases of chondrules variably comprise turbid material and microcrystalline (1-5 μm) grains. Plagioclase feldspar occurs as microcrystallites (rarely exceeding 5 μm in diameter) within chondrules and matrix. Accessory silicate minerals in Wooramel include rare grains of polysynthetically twinned clinopyroxene and diopside.

The microstructure of Wooramel and the presence of equilibrated mineral assemblages are consistent with petrologic type 5 of the Van Schmus and Wood (1967) classification. Minerals in Wooramel show evidence of extensive shock and reheating. Under crossed polars, silicates display marked undulose extinction and some grains of olivine show incipient mosaicism. Locally, there are veins and pockets of melted silicates, up to 50 μm across, comprising crystal fragments set in a turbid, brown silicate glass. Maskelynite was not observed. However, grains of plagioclase are generally too small to be resolved clearly under the microscope. Overall, the level of shock alteration of silicates corresponds to 'facies d-e' of the Dodd and Jarosewich (1979) classification.

Particles of metal and troilite have been extensively shock-melted causing localised 'blackening' of the meteorite. The melted material has been injected into the surrounding silicates as droplets and veins (Figure 3a). Frequently, grains of kamacite show partial, or complete 'massive' transformation to ragged α_2-kamacite (Figure 3b).

Mount Margaret contains prominent chondrules set in a crystalline matrix. The total iron content (22.40 wt %) of the meteorite and compositions of the constituent ferromagnesian silicates (olivine $Fa_{24.0}$; orthopyroxene $Fs_{20.9}$ $Wo_{1.1}$) show that Mount Margaret belongs to the L-group of chondrites. Microcrystalline plagioclase feldspar, uniform silicate compositions, and the presence of rare grains of polysynthetically twinned clinopyroxene and diopside ($Fs_{8.3}$ $En_{52.3}$ $Wo_{39.4}$) indicate that Mount Margaret is petrologic type 5. Minor alteration of minerals in Mount Margaret as the result of shock-loading (Table 1) correspond with 'facies b' of the Dodd and Jarosewich (1979) classification.

Nimberrin is a thoroughly recrystallized chondrite containing indistinct relic chondrules in a coarsely crystalline matrix. The compositions of olivine ($Fa_{25.5}$) and low-Ca orthopyroxene ($Fs_{22.3}$ $Wo_{1.0}$) are homogenous and within the range of L-group chondrites. Accessory minerals include diopside ($Fs_{8.9}$ $En_{47.9}$ $Wo_{43.2}$). The degree of recrystallization of Nimberrin is consistent with petrologic type 6 of the Van Schmus and Wood (1967) classification.

Extensive and severe shock alteration of minerals throughout the meteorite (Table 1), including the general conversion of plagioclase feldspar to maskelynite and abundant pockets of shock-melted silicate, are consistent with 'facies d' of Dodd and Jarosewich (1979). In addition, grains of metal and troilite have been extensively melted, α-kamacite has been recrystallized to equiaxial units (Figure 3c), and there is abundant plessite ($\alpha + \gamma$).

Millrose is a highly recrystallized chondrite comprising rare chondrule relics in a granular, crystalline inter-chondrule matrix. Olivine and low-Ca orthopyroxene with uniform compositions of $Fa_{24.8}$ and $Fs_{21.4}$ $Wo_{1.5}$, respectively, classify Millrose as an L-group chondrite. The degree of recrystallization of the chondrite is consistent with petrologic type 6 of the Van Schmus and Wood (1967) classification.

Severe alteration of silicate minerals in Millrose resulting from shock-loading (Table 1) include undulose extinction, partial conversion of plagioclase to maskelynite and melt-pockets. Additionally, metal and troilite have been shock melted and grains of α-kamacite have been locally converted to α_2-kamacite.

Table 3. Bulk chemical analyses and normative compositions of the Baandee, Jeedamya, Mount Margaret and Wooramel ordinary chondrites.

	Wt% (ppm)	Baandee	Jeedamya	Mt. Margaret	Wooramel (measured)	***Wooramel (recalc.)
Non-magnetic, attacked (Sulphides)	Fe	2.68	2.67	2.32	2.61	2.61
	Cr	(<1)*	(<1)	(<1)	(<1)	(<1)
	Ti	(<5)	(<5)	(<5)	(10)	(10)
	Mn	(29)	(73)	(41)	(70)	(70)
	S	1.63	1.94	1.53	1.29	1.29
	Cu	(33)	(13)	(13)	(45)	(45)
	Zn	(15)	(4)	(7)	(25)	(25)
	Ge	(<0.5)	(<0.5)	(<0.5)	(3)	(3)
	Ga	(<0.5)	(0.6)	(0.2)	(<0.1)	(<0.1)
Magnetic, attacked (Ni-poor metal and schreibersite)						bulk metal
	Fe	18.21	17.80	9.53	1.02	9.97
	Ni	1.34	1.38	0.70	0.86	1.42
	Co	(756)	(800)	(510)	(310)	(313)
	Ge	(4.8)	(5.6)	(3.7)	(<0.1)	(<0.1)
	Ga	(3.7)	(1.5)	(0.3)	(<0.1)	(<0.1)
	P	(7)	(5)	(3)	(165)	(165)
	Si	(25)	(24)	(8)	(22)	(22)
						Cu (3)
Magnetic, unattacked (Ni-rich metal)	Fe	0.91	0.51	0.94	0.071	
	Ni	0.56	0.32	0.59	0.039	
	Co	(33)	(42)	(66)	(3)	
	Cu	n.d.	(56)	(78)	(3)	
	Ge	n.d.	(1.4)	(3.1)	(<0.1)	
	Ga	(7.6)	(0.3)	(0.3)	(<0.1)	
Non-magnetic, unattacked (silicates, phosphates, oxides)	SiO_2	35.90	36.49	39.87	39.30	41.56
	TiO_2	0.08	0.12	0.20	0.20	0.21
	Al_2O_3	1.84	1.92	2.04	1.95	2.06
	Cr_2O_3	0.54	0.59	0.56	0.60	0.63
	FeO	9.49	9.39	12.36	11.80	12.48
	Fe_2O_3	-	-	-	12.70	-
	NiO	-	-	-	0.66	-
	MgO	23.19	23.24	25.45	22.80	24.11
	MnO	0.28	0.28	0.33	0.15	0.20
	CaO	1.66	1.52	1.73	1.89	1.98
	Na_2O	0.73	0.76	0.88	0.62	0.65
	K_2O	0.10	0.10	0.10	0.09	0.10
	P_2O_5	0.25	0.25	0.22	0.25	0.26
	H_2O^+	0.27	0.19	0.19	1.11	0.30
	H_2O^-	0.03	0.05	0.04	n.d.	n.d.
	C	0.06	0.03	0.03	0.10	0.10
	Ge	n.d.	(<0.5)	(1.0)	(35)	(35)
	Ga	(<0.5)	(2.9)	(2.3)	(9)	(9)
	Totals	99.84	99.65	99.68	100.18	100.00

	Wt% (ppm)	Baandee	Jeedamya	Mt. Margaret	Wooramel (recalc.)
Weight ratios**	Fe_T%	29.18	28.28	22.40	22.28
	Fe^o/Fe_T	0.65	0.62	0.45	0.45
	Fe_T/SiO_2	0.81	0.78	0.56	0.54
	SiO_2/MgO^2	1.55	1.57	1.57	1.72

NORMS (wt %)

	Baandee	Jeedamya	Mt. Margaret	Wooramel
Metal	20.9	19.4	11.5	11.4
Troilite	4.5	5.3	4.2	3.9
Or	0.6	0.6	0.6	0.6
Ab	6.2	6.4	7.4	5.5
An	1.4	1.5	1.3	2.4
Di	4.1	3.5	4.7	3.5
Hy	27.4	29.7	27.9	42.4
Ol	32.8	31.2	40.1	27.7
Chr	0.8	0.9	0.8	0.9
Il	0.2	0.2	0.4	0.4
Ap	0.6	0.6	0.5	0.8
Others	0.5	0.6	0.4	0.4
Total	100.00	99.9	99.8	100.00
Fa^t	18.1	17.8	20.7	22.8
An	16.5	16.8	13.3	
Ni	9.1	8.8	11.3	12.4

Notes: * Figures in brackets are parts per million;
n.d. = not determined
** Fe_T = total iron; Fe^0 = **metallic iron**
Fa = atom % Fe/ (Fe+Mn+Mg) in normative olivine and pyroxene
An = mol% An/ (Or+Ab+An) in normative feldspar

*** recalculated Wooramel analysis; Fe_2O_3 and NiO recalculated as metal, excess water removed and oxide fraction recalculated to 100%

(Analyst R.O. Pepper)

Estimation of levels of shock alteration

It is widely accepted that most of the mechanical damage and re-heating effects displayed by the minerals in chondritic meteorites are related to shock events which post date their formation, primary crystallization and cooling (e.g., Heymann 1967; Dodd and Jarosewich 1979). Estimates of the P/T relationships indicated by mechanical and thermal damage to minerals in naturally shocked chondrites have been made by comparison with experimentally shock-loaded meteoritic (Fredricksson *et al.* 1963; Sears *et al.* 1984), terrestrial (Stöffler 1972 and 1974) and synthetic (Zukas and Fowler

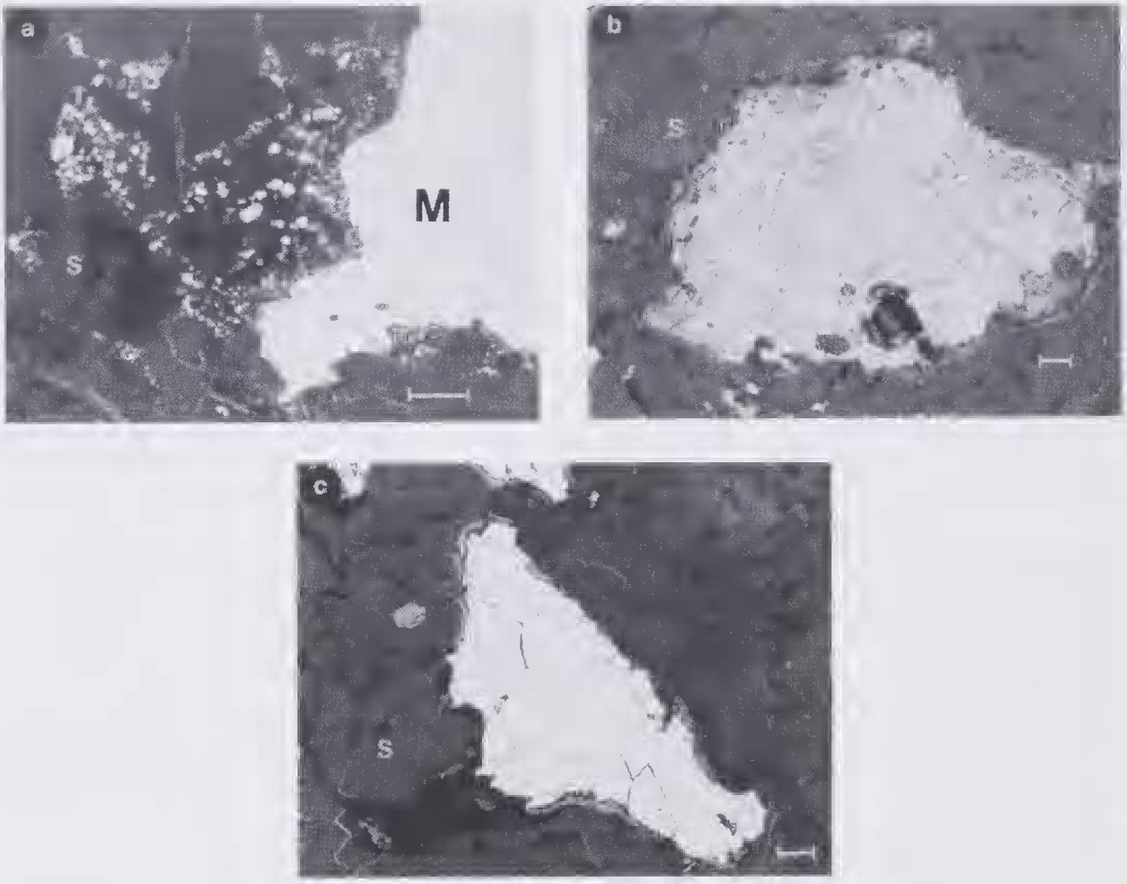

Figure 3a. Incipient melting of metal (M), troilite (T) and silicates (S) in the Wooramel meteorite.

3b. Grain of kamacite in Wooramel showing Neumann bands and partial transformation to 'ragged' α_2-kamacite along the boundary with silicates (S) (2% nital etch).

3c. Kamacite in Nimberrin recrystallized to equiaxial units showing good 120° triple junctions. (2% nital etch). Scale bars = 10 μm.

1961; Zukas 1969) materials. Compressive shock-loading of materials is accompanied by adiabatic heating. Following the passage of the shock wave, rarefaction and decompression cools the material to a 'residual' temperature. Subsequently, the material cools by radiation and conduction, the rate of cooling depending on the insulation of the material.

All the chondrites in the present study display, to varying degrees, the effects of alteration by shock-loading. The extent and nature of alteration to chondritic materials caused by shock, or shock reheating, depends on the scale of mechanical damage, peak temperature during shock and the rate of cooling following shock (Sears *et al.* 1984). In the six meteorites studied, the absolute rates of cooling after shock are unknown. However, from the observed microstructural indicators of shock displayed by each meteorite it is possible to establish rough limits for the magnitude of the shock event, the peak shock temperature, and also the relative rates at which the material cooled.

In Baandee, Jeedamya and Mount Margaret, silicate minerals show weak undulatory extinction, troilite displays deformation twins and Neumann bands are present in grains of kamacite. These features are the result of low temperature, pressure induced damage consistent with mild shock-loading to pressures of $<$10-15 Gpa (Sears *et al.* 1984). Although temperatures in these meteorites may have been raised slightly during shock compression they cannot be estimated accurately, but were certainly less than 500 ^{0}C (Raikes and Ahrens 1978). The absence of evidence of recrystallization in mechanically deformed metal indicates that post shock cooling rates in Baandee, Jeedamya and Mount Margaret were rapid.

In Wooramel, Nimberrin and Millrose, silicate and metallic minerals show evidence of both mechanical and thermal damage. In Wooramel, the presence of abundant α_2-kamacite throughout the body of the meteorite and which probably formed by the reaction $\alpha \rightarrow \gamma \rightarrow \alpha_2$ (Axon 1967), indicates severe transient re-heating to temperatures in excess of 800 ^{0}C followed by rapid cooling. However, to account for the extensive incipient melting and mixing of metal, troilite and silicates, much higher temperatures must have been achieved locally during shock compression. It is probable that attenuation of shock waves at grain boundaries caused localised melting where peak shock temperatures must have risen to 900-1000 ^{0}C. Sears *et al.* (1984) demonstrated that, in chondritic meteorites, troilite is a 'shock absorber', often inducing locally high temperatures under conditions of shock-loading. Overall, the mechanical and thermal damage in Wooramel is consistent with shock-loading to pressures of approximately 30 Gpa (Sears *et al.* 1984).

In Millrose, incipient transformation of kamacite to α_2 and shock melted metal, troilite and silicates indicate a level of shock alteration similar to Wooramel. However, despite extensive shock melting, silicates in Millrose have not been 'blackened' by the shock event, and pockets of shock melted material are less abundant than in Wooramel. Although temperatures in Millrose during shock-loading undoubtedly rose to 800-1000 ^{0}C, cooling from peak shock temperatures was rapid. The extent of shock damage in Millrose is consistent with shock-loading in the range 25-30 Gpa (Sears *et al.* 1984).

Compared with Wooramel and Millrose, Nimberrin displays similar levels of alteration by shock-loading, but a more complicated thermal history. In Nimberrin, the occurrence of kamacite which has been recrystallized to equiaxial units (Figure 3c), and abundant plessite (α+γ), indicates a period of prolonged annealing at temperatures in excess of 500 ^{0}C (Axon, 1967; Wood, 1967). The nature of the alteration of kamacite is consistent with recrystallization of mechanically deformed and shock hardened metal (Axon 1967). Extensive melting of metal, troilite and silicates throughout the meteorite testify to local peak shock temperatures in the range 900-1000^{0}C. Unfortunately, deep weathering of particles of metal in Nimberrin has obscured some of the metallographic features, particularly along grain boundaries. Evidence of α_2 transformations, which might have post dated the recrystallization of kamacite were sought, but not found.

The textural features of metal in Nimberrin signify that cooling from the peak shock temperature was moderate to slow. This allowed mechanically deformed kamacite to recrystallize, and taenite to decompose to plessite ($\alpha+\gamma$). Alternatively, Nimberrin may have undergone more than one period of shock, heat treatment and cooling.

Summary and conclusions

The six meteorites described here bring the total number of documented and distinct meteorites from Western Australia to 120. The meteorites; Baandee (H5), Jeedamya (H4), Mount Margaret (L5), Wooramel (L5), Nimberrin (L6) and Millrose (L6), are all ordinary chondrites. The meteorites display varying degrees of alteration attributable to pre-terrestrial shock-loading appropriate to facies b (Baandee, Jeedamya, Mount Margaret), facies d (Nimberrin and Millrose) and facies d-e (Wooramel) of the Dodd and Jarosewich (1979) classification.

Comparisons with experimentally shocked meteoritic (Sears *et al.* 1984) and terrestrial (Reimold and Stöffler 1978) materials indicate magnitudes (P/T) of shock-loading ranging from <10 Gpa and <500 °C (facies b) to >30 Gpa and 800-1000 °C (facies d-e). The microstructures of metallic minerals in those meteorites displaying the effects of appreciable shock reheating indicate rates of cooling following shock which vary from fast (Wooramel and Millrose) to moderately slow (Nimberrin), and serve to emphasize the enormous range of alteration which may be encountered in shocked meteorites.

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